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by Donald W. Smith and Bedford A. Lampkin

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SUMMARY

The capability of a spacecraft navigator to make in-flight navigation measurements from on board the spacecraft using a hand-held sextant has been studied extensively. Tests conducted on board the orbiting Gemini XII spacecraft were designed to determine the effect of the actual space-flight environment on navigator performance. The results show that: (1) hand-held sextant measurement performance is excellent providing a standard deviation of measurement error less than 10 arc seconds; (2) spacecraft rotational motion and the actual spacecraft environment had little effect on the navigator performance; and (3) window-induced measurement errors in the Gemini XII spacecraft were small and predictable. The optical hand-held sextant appears to have application to on-board navigation for future manned space flights.

INTRODUCTION

Earth-based electronic tracking systems have been used for earth orbital navigation of the manned Gemini spacecraft and for translunar and interplanetary navigation of various unmanned spacecraft. It is planned to use these tracking systems as an element in the primary navigation system for the manned Apollo spacecraft. In the manned vehicles, these systems provide accurate navigation measurements and relieve the crew workload at critical time periods in the mission.

Studies of circumlunar navigation (refs. 1 and 2) and interplanetary navigation (refs. 3 and 4) have indicated that precise angular measurements (standard deviation of measurement error $\leq$ 10 arc sec) made with an optical device such as a sextant or theodolite can be suitably processed in a computer mechanized navigation system to provide satisfactory midcourse navigation. Early in the space-flight era, similar studies led technical planners to consider on-board systems for primary navigation. A simplified highly reliable on-board navigation system for manned orbital, lunar, and interplanetary space flight is desirable:

1. To provide a backup capability suitable for safe earth return from a variety of mission phases

2. To provide a blunder check for primary system errors

3. To inspire the crew's confidence in the performance of the primary navigation and guidance system.

On-board navigation of aircraft and ships has evolved into a system that depends to a large extent on the use of appropriate tables and charts, a sextant, a clock, and a simple computational form to establish vehicle position on the earth's surface. These simplified systems are capable of providing a position determination within a mile. However, the navigation of spacecraft that travel at high speeds over large distances where the consequences of small navigation errors would be greatly magnified requires systems based on new standards of precision in both sighting and calculation.

The problem of sighting precision is being studied in actual space flight by the Air Force (ref. 5) and NASA (ref. 6). Sighting precision has also been studied in simulators (refs. 7, 8, and 9) and in high-flying aircraft (ref. 10). The results of the limited space flight and more comprehensive simulator and aircraft experiments indicated that a hand-held sextant could be used as a major element of a spacecraft navigation system.

The general objective of Ames' T002 in-flight experiment was to make navigation measurements through the window of the stabilized Gemini spacecraft with a hand-held sextant:

1. To evaluate the astronaut's ability to make accurate space navigation measurements using a simple instrument in an authentic space environment
2. To examine the operational feasibility of the measurement technique both with pressure suit helmet off and pressure suit helmet on - visor down
3. To evaluate operational problems associated with the spacecraft environment
4. To validate ground-based simulation techniques by comparison of the in-flight data with baseline data obtained by the spacecraft pilot, both in simulators and using actual celestial targets from ground observatories.

The T002 experiment results are compared with baseline data obtained in a ground-based simulation and with other flight data, and the potential of the hand-held sextant for implementation of on-board navigation systems for interplanetary flight is examined.

EQUIPMENT

Sextant Description

The two line-of-sight (LOS) sextant shown in figure 1 was used in the T002 experiment. It was designed to measure accurately the angle between various types of celestial targets.

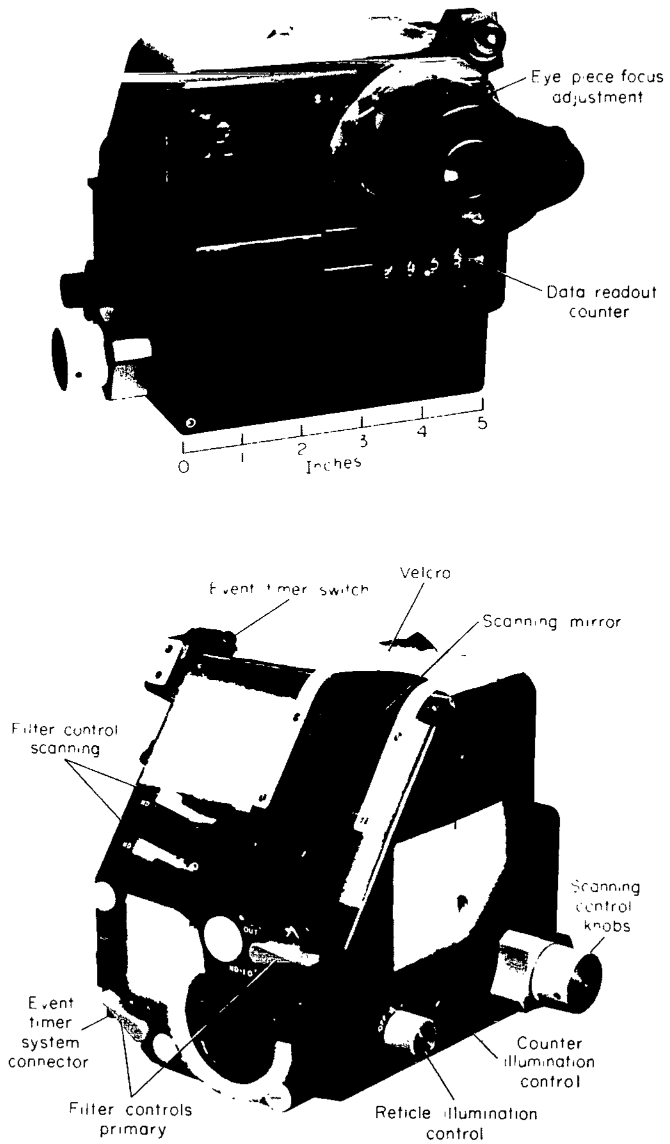

Figure 1.- Hand-held space sextant used in T002 experiment.

The view through the fixed LOS field of the sextant is imaged in its focal plane through a plate beamsplitter, objective lens, and prism-mirror erecting system (fig. 2). The view through the scanning LOS field is reflected from an articulated scanning mirror; it is then combined with the fixed LOS field in the beamsplitter and imaged (in the focal plane) by the same objective lens and erecting system. The operator, by observing the focal plane through the eyepiece and adjusting the scanning fields of view can superimpose the selected targets in the fixed and scanning fields of view, and thus establish the angular separation of the targets. The angular rotation of the scanning mirror is controlled by the two-speed scanning control knobs, which provide target optical motions of 1 degree and 5 degrees per revolution of the knobs.

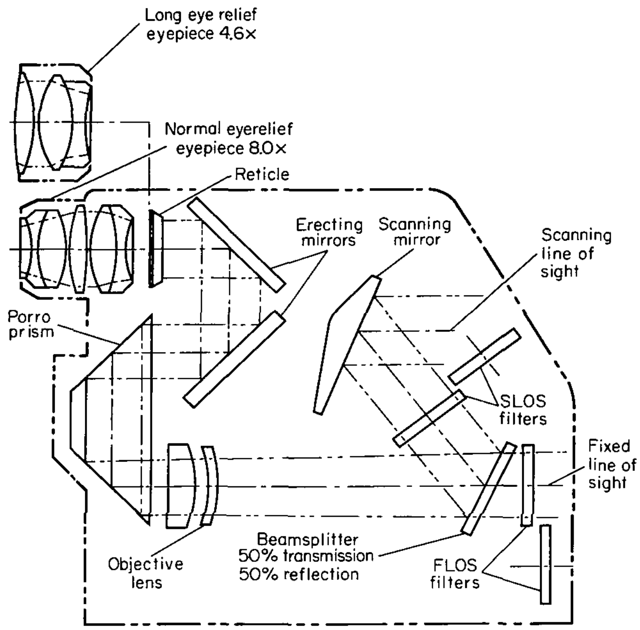

Figure 2.- Schematic diagram of optics; hand-held sextant.

An engraved reticle is located at the principal focus of the telescope objective lens. The reticle pattern was designed to assist the operator in keeping the targets alined in the measurement plane of the instrument while making the sightings. The reticle also defined the area of the instrument field of view in which measurements were to be made to minimize measurement errors. Reticle illumination is provided to enable the operator to see the reticle against a dark background.

The sextant is equipped with two removable eyepieces, one providing normal eye relief, and the other, long eye relief. The normal eye relief eyepiece is used when the sextant can be brought directly to the eye for viewing, while the long eye relief eyepiece allows the sextant to be used with the pressure suit helmet on and the helmet visor down.

Data readout is accomplished by direct reading of a mechanical counter located below the instrument eyepiece. The measured angle between the fixed and scanning LOS is indicated on the counter in degrees, the least count being 0.001° or 3.6 arc seconds.

A dual-cell rechargeable nickel-cadmium battery, contained within the sextant, provides 2.5 volts for illuminating both the data readout and the reticle.

An event timer button and switch are located on the right side of the instrument. The event timer switch was connected to the Gemini XII spacecraft telemetry recorder through the spacecraft utility cord. Depression of the event timer button put a time-correlated signal on the on-board pulse code modulation (PCM) data recorder tape for use in the data analysis.

Two filters of different density are provided in each LOS to reduce the amount of light transmitted through them. The purpose of the filters is to permit viewing of images of widely varying brightness.

The general characteristics of the sextant are as follows:

Size	7 × 7-1/4 × 6-1/16 in.
Weight	
Normal eye relief eyepiece	6 lb 4 oz
Long eye relief eyepiece	6 lb 0 oz
Magnification	
Normal eyepiece	8×
Long eye relief eyepiece	4.6×
Field of view	7°
Exit pupil	
Normal eye relief eyepiece	4 mm
Long eye relief eyepiece	7 mm
Eye relief	
Normal eye relief eyepiece	18 mm
Long eye relief eyepiece	60 mm
Diopter adjustment	
Normal eye relief eyepiece	-3 to +5
Long eye relief eyepiece	-3 to +3
Resolution	7 sec of arc
Image	Erect
Range	76°

A detailed description of the instrument, the results of the flight rating program, and results of the functional verification program are presented in reference 11.

Sextant Calibration

Preflight.- The flight sextant (GFAE No. EG 25100-1, serial no. 4) was calibrated prior to the flight of the Gemini XII using the Acceptance Test and Optical Calibration Procedure (KTS 41580 00 001) of reference 12. The sextant calibration error, ε_c, is the average of the errors obtained at each discrete indicated sextant angle reading (every 1° from -6° to +70°) in three consecutive calibrations. The range of the three instrument errors measured at each indicated sextant angle during the calibration was always less than 6 arc seconds. For an actual true target angle of 0° the sextant was carefully alined on an optical bench to indicate 0° on the sextant readout counter. To obtain the actual measured sextant angle, the instrument error is added algebraically to the indicated sextant angle (fig. 3).

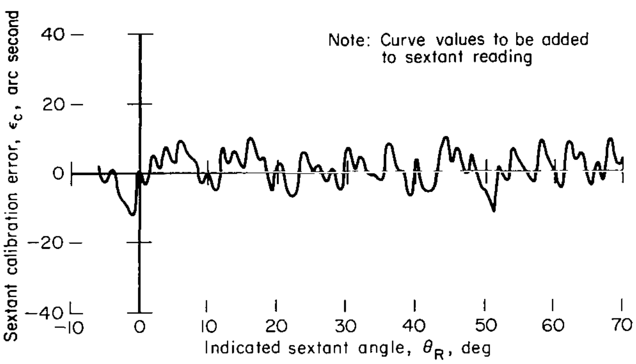

Figure 3.- Preflight calibration of hand-held space sextant (GFAE No. EG25100-1, serial no. 4).

Postflight.- After the Gemini XII flight, the sextant was visually inspected and calibrated to determine whether exposure to the space and spacecraft environment had any deleterious effects on the sextant or its performance. The inspection revealed no change in the physical condition of the instrument. The sextant was calibrated using the procedure of reference 12, but only in the restricted ranges of indicated sextant angles, from 0 to 3°, 6.5° to 9.5°, and 16.5° to 19.5°, in which sighting measurements were made during the Gemini XII flight. A calibration for the range from 31.5° to 34.5° was also made to check a similar preflight calibration. Figure 4 compares the postflight calibration data with the preflight data of figure 3 and with the calibration made in the range of sextant angles from 0° to 3°. Two special postflight calibrations were made for indicated sextant angles of 7.525° and 18.605°, the approximate measured angles of the sightings performed on the Gemini XII flight.

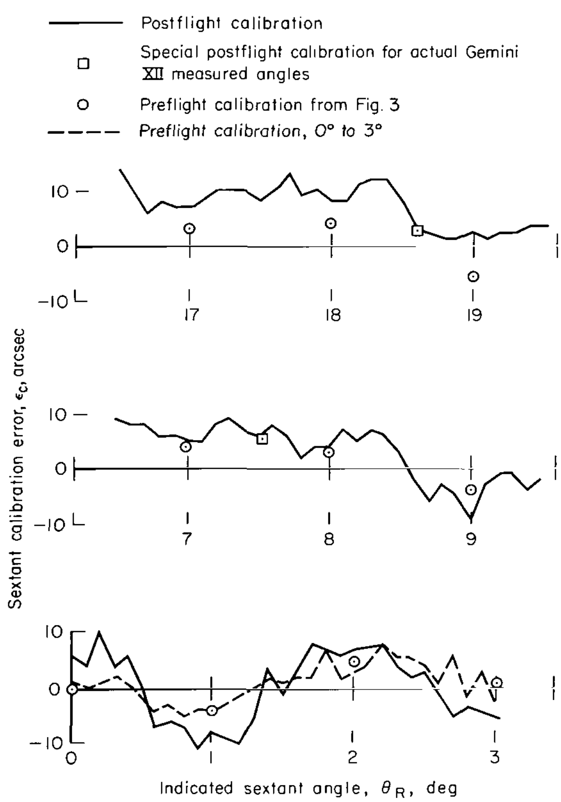

Figure 4.- Postflight calibration of hand-held space sextant (GFAE No. EG25100-1, serial no. 4).

From examination of figure 4, it may be seen that the postflight and preflight sextant calibration errors differ generally by about 5 arc sec with a few as large as 10 arc sec. Except for the few larger errors, the calibrations meet the acceptance test requirements for operational use of the sextant (ref. 12, appendix II, para. 9.18): the difference between the maximum and minimum error at any data point (indicated sextant angle) shall not exceed 6 arc sec. It seems reasonable to conclude, therefore, that the exposure to the space-flight environment had little or no effect on the performance of the sextant.

Event Timing System

The integral event timer switch (fig. 1) was actuated by the pilot when he attained target superposition in the sextant field of view. Actuation of the switch initiated a time-correlated electrical signal to an on-board PCM tape recorder. This event timing system was capable of providing the time of each sextant sighting with an error less than ± 0.2 sec. The data were stored on the tape and transmitted to the ground via telemetry equipment at a future time. It then became available for reduction of the sighting data.

In a previous experiment on Gemini IV (ref. 5), time correlation data were lost as the result of an equipment failure, which seriously restricted the usefulness of the data collected and recorded in the pilots log and, in this case, made it impossible to obtain quantitative results. To prevent data loss in this experiment, a backup timing system was devised in which the command pilot manually logged the time of sextant sighting, which he read from a spacecraft elapsed time clock on an oral "MARK" command from the pilot. This system proved accurate within about ± 0.6 sec based on the event times successfully telemetered from the primary system during the flight.

Sextant Stowage

During the launch and entry phase of the Gemini XII mission, the sextant was stowed between the pilots in a special container shown in figure 5. This container restrained the sextant during these high acceleration flight regimes and also protected the instrument from damage due to both the sustained acceleration and vibration loads.

During the orbital flight phase, the instrument was stowed above the back of the command pilot's seat where it was restrained from moving by means of Velcro pads.

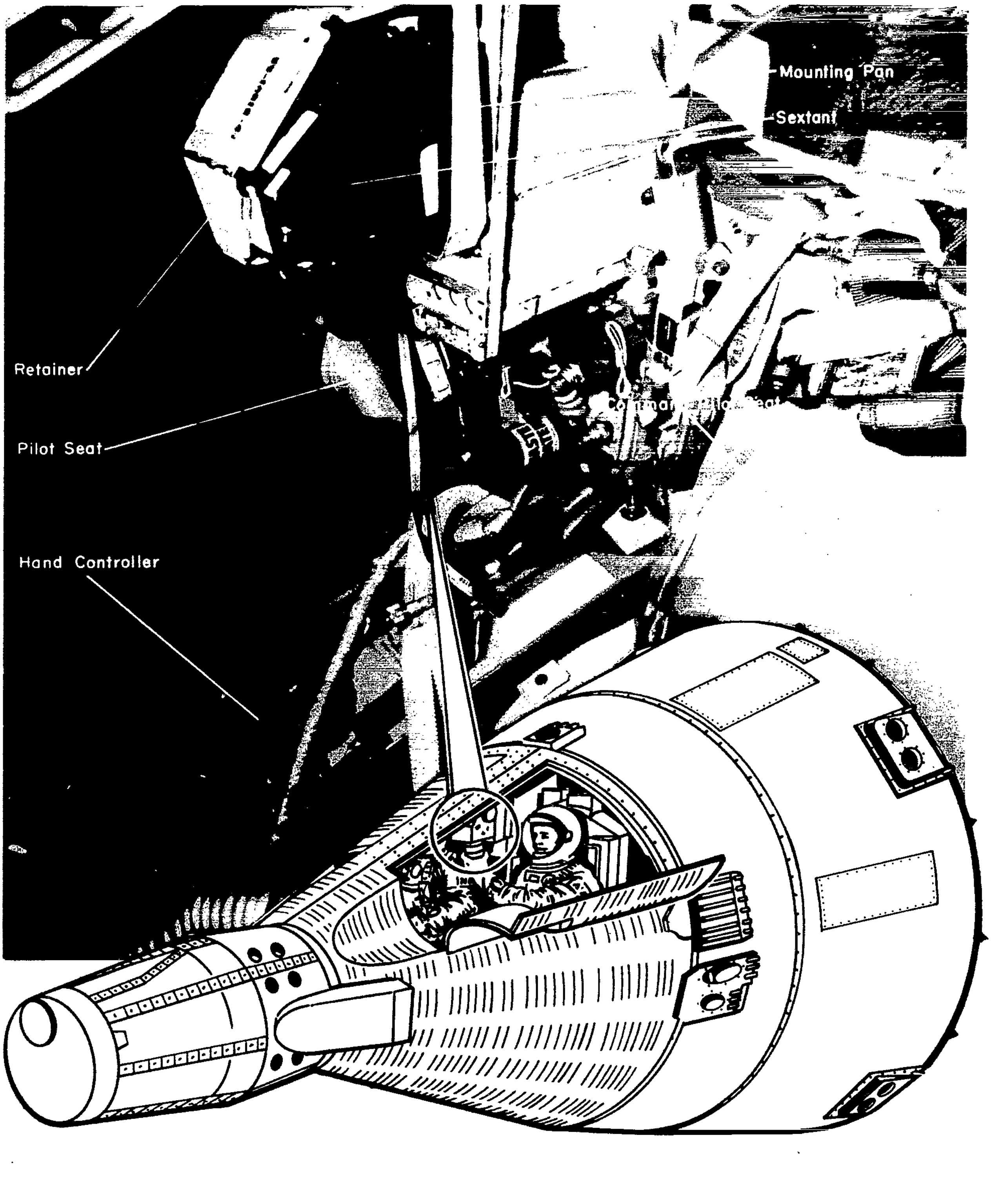

Figure 5.- Stowage of sextant on board Gemini XII spacecraft.

EXPERIMENTAL METHODS AND PROCEDURES

Preflight Training

Training is a critical factor in developing the ability of a spacecraft navigator to make accurate navigation measurements (ref. 7). The Gemini XII pilot, Major Edwin Aldrin, was trained for the T002 experiment in the Gemini cab of the Docking Simulator at NASA's Manned Spacecraft Center (fig. 6). Two simulated star targets were installed in the simulator room. The star targets consisted of 12-in. parabolic mirrors that projected collimated light toward the sighting station simulating a star magnitude of about 2. Using the hand-held sextant in the darkened Docking Simulator, the pilot performed 15 consecutive measurements of the angle between the simulated stars. A zero bias correction was obtained by having the pilot take 10 consecutive measurements when sighting on one star with both sextant LOS. The measured sextant angles were read off of the sextant counter and recorded. Sextant measurements were repeated in 15 sighting sessions distributed over a period of 4 days.

Preflight Baseline Experiments

Accurate reference baseline data were required for evaluating the effect of the space-flight environment on the pilot's ability to make accurate sextant measurements. All baseline data were obtained at Ames Research Center primarily in the Ames Midcourse Navigation and Guidance Simulator (ref. 7). The basic components of the simulator are a visual scene (moon-star field) and a movable cab (manned space vehicle). The cab was static for the majority of the sighting sessions. Cab motion appeared to have no effect on sighting performance. The two simulated stars used in the initial training were employed in obtaining the baseline data. Using the hand-held sextant, the Gemini XII pilot made 5 consecutive measurements of the angle obtained when viewing the same simulated star through both sextant LOS to establish an instrument-operator measured zero bias. Subsequently, 10 consecutive measurements of the angle between the selected sighting targets were made from which the mean and standard deviations of the measurement errors were computed. Measurements were made with the helmet off (normal eye relief eyepiece) and helmet on, visor down (long eye relief eyepiece). Sextant measurements were made in 25 sighting sessions distributed over a period of 2 days.

The true angles between the simulator sighting targets were measured using a Hilger Watts No. 2 Microptic Theodolite with a 0.1 arc sec readout and an error of less than 1 arc sec.

Baseline data were also obtained at the Ames ground sighting station using real stars. Measurements were made in 5 sighting sessions distributed over a period of 2 days.

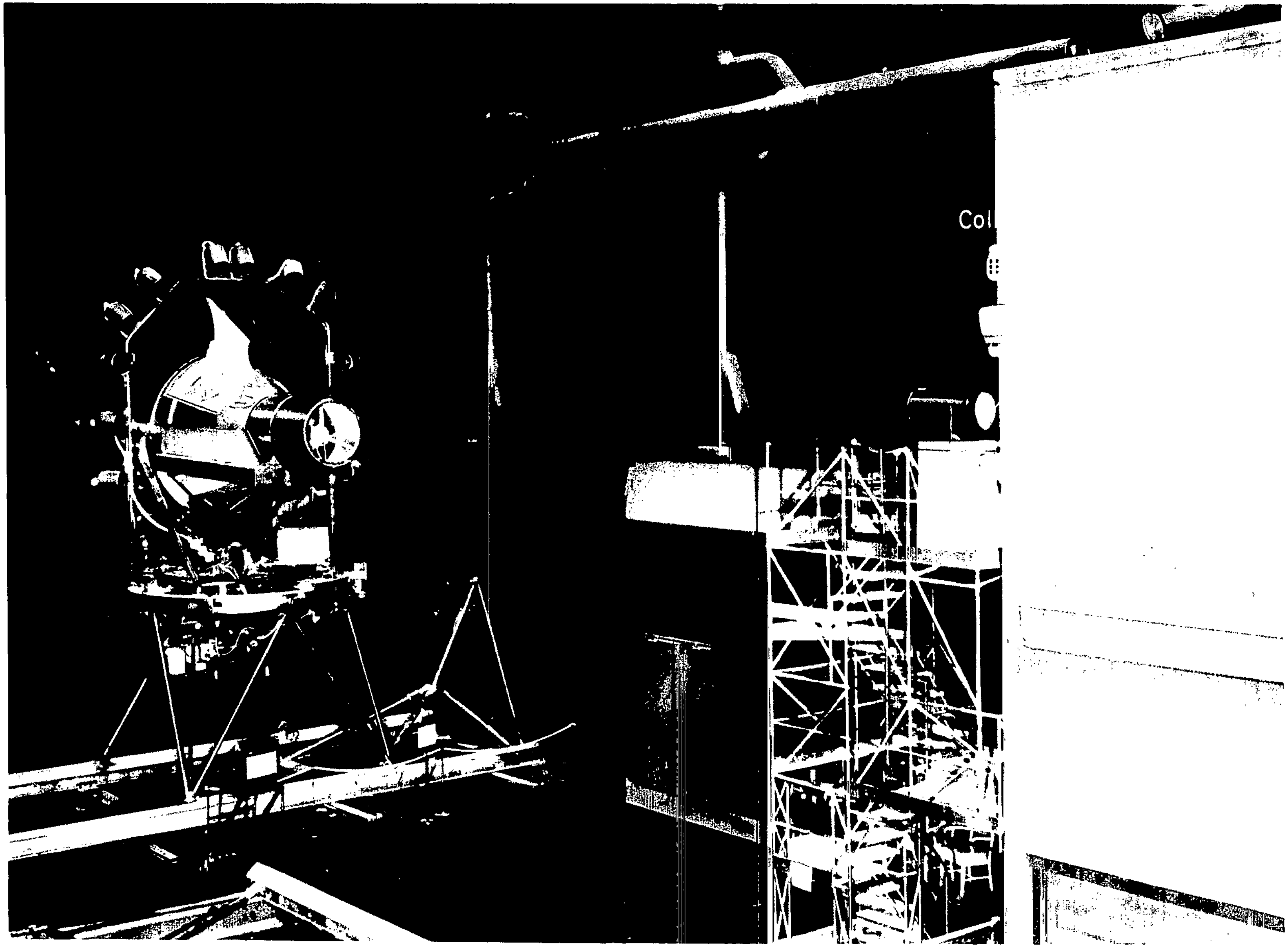

Figure 6.- MSC docking simulator used in preliminary astronaut training.

The sextant event timing system was used to mark the time of sextant measurement on a digital recorder. An electronic clock synchronized to the national time standard transmitted over radio station WWV was used as the time reference. Timing error was less than ±0.25 sec.

In-Flight Experiment

In-flight procedures were carefully formulated by the experimenters and the flight crew in the Gemini Mission Simulator at the Manned Spacecraft and Kennedy Space Centers. The methods for acquiring the target, taking data, measuring time of targets superposition, and locating sextant LOS on the window were simplified to assure a maximum probability of experiment success. These procedures were frequently practiced by the crew using the visual scene of the Mission Simulator.

The sextant was taken from its stowed location between the pilot and the command pilot. The spacecraft commander then established the spacecraft orientation with respect to the selected star targets so that the pilot could see them through the right-hand window (fig. 7). The spacecraft was stabilized to this orientation within about ±2° in pitch and yaw and ±10° in roll with very low residual attitude rates (less than 0.10° per sec). After the spacecraft was stabilized, the pilot brought the sextant to the window as shown in figure 7, set the reticle illumination to a comfortable level, and acquired the targets in both LOS. The pilot then superimposed the target images and marked the time of superposition by depressing the sextant event timer button. An oral time "MARK" was called out by the pilot, and the spacecraft commander read his spacecraft clock, noting the time in the experiment log along with the measured angle read from the sextant by the pilot. This procedure was repeated for at least 13 consecutive measurements of the angle between the target pair and 5 times for a single star (the same star in each LOS) to provide an indication of the measured zero bias of the instrument-operator combination.

During each sighting session, the command pilot determined and noted on a diagram contained in his log, the point on the window that would be intercepted by the extension of the lower left corner of the sextant case. This point was used by the experimenter in correcting the data for window-induced errors.

The procedure was well executed by the crew and although some of the telemetered time data were lost, the backup time "MARK" procedure provided adequate redundant data.

Data Reduction

The sighting performance of the pilot was evaluated using three criteria: (1) sighting measurement error; (2) the mean or arithmetic average of a group of sighting measurement errors; and (3) the standard deviation of

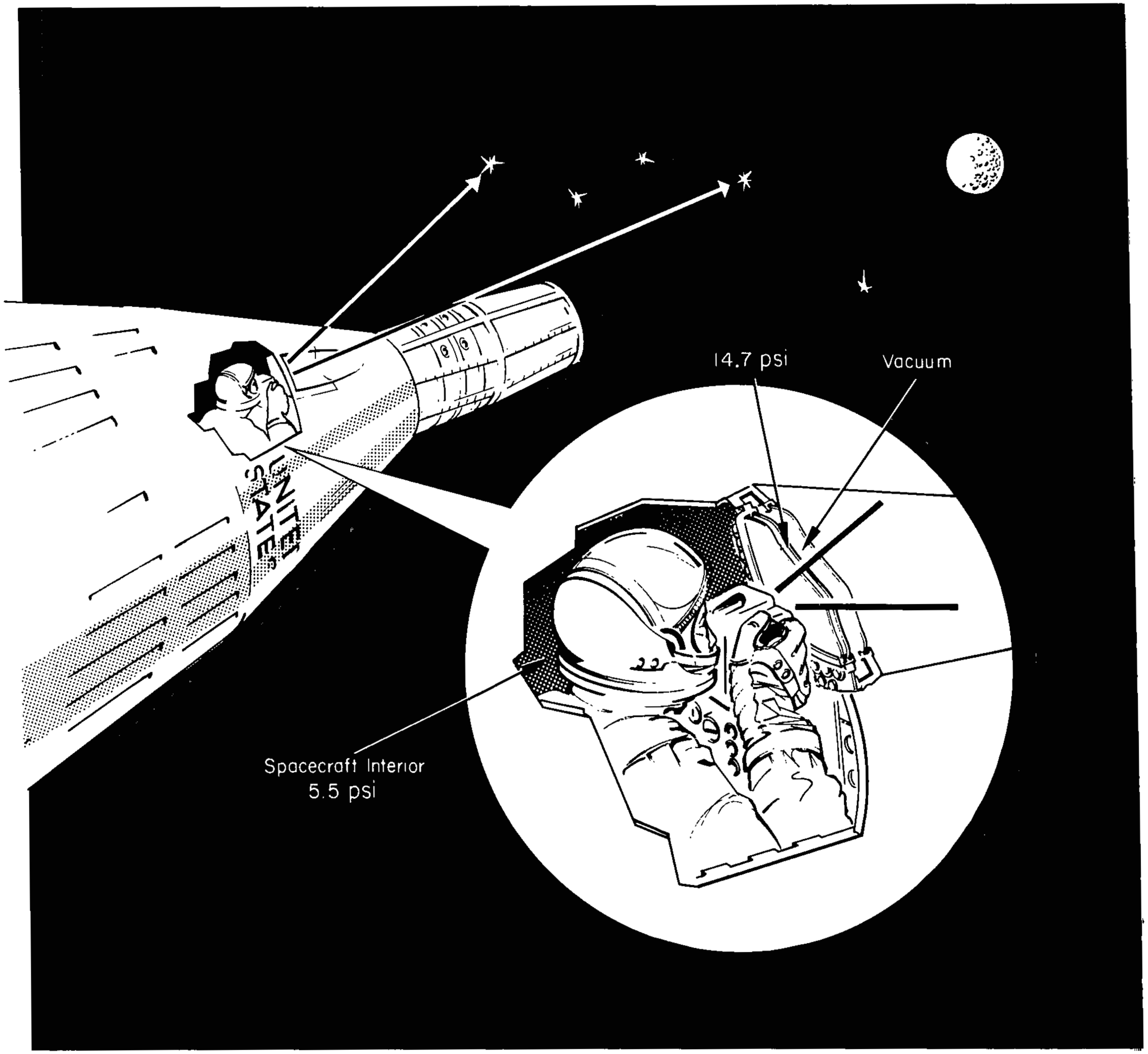

Figure 7.- Sextant sighting experiment on Gemini XII spacecraft.

the group of sighting measurement errors about their mean value. The computation of the values of these criteria was accomplished using the equations and corrections explained below.

Sighting measurement error.- The sextant sighting measurement error values ε (in arc sec) were computed as follows:

$$\varepsilon = (\theta_M - \theta_T) - (\theta_Z)_{mean} = \text{sighting measurement error} \tag{1}$$

$$\theta_M = \theta_R + \varepsilon_c = \text{measured target angle} \tag{2}$$

θ_R = sextant readout counter reading

ε_c = sextant calibration error (from fig. 3)

$$\theta_T = \theta_S + \varepsilon_W + \varepsilon_R = \text{true target angle} \tag{3}$$

θ_S = celestial target angle (computed)

ε_W = window-induced measurement error (determined both experimentally and analytically)

ε_R = error due to the difference of the index of refraction of the light transmitting media within (n_2) and outside (n_1) of the spacecraft

$= \sin^{-1}\left(\frac{n_1}{n_2} \sin_{\alpha_1}\right) - \alpha_1$ (ref. 13)

n_1, n_2 = index of refraction

α_1 = angle between the incident light ray from the star and the window normal

$(\theta_Z)_{mean}$ = mean measured zero bias

θ_Z = the measured zero bias or the measured angle when the same star is viewed in each LOS

The mean measured zero bias is used to correct the measurement data for possible mechanical changes in the sextant due to environmental changes as well as possible changes in the pilot's vision.

Mean sighting measurement error.- The mean sextant sighting measurement error values ε_{mean} (in arc sec) were computed as follows:

$$\varepsilon_{mean} = (\theta_M - \theta_T)_{mean} - (\theta_Z)_{mean} \tag{4}$$

ε_{mean} = mean sighting measurement error

Standard deviation of sighting measurement error.- The standard deviation of the sighting measurement error, σ_ε, presented in this report was computed using equation (5).

$$\sigma_\varepsilon = \sqrt{\frac{\sum_{i=1}^{n} \left[(\theta_M - \theta_T) - (\theta_M - \theta_T)_{mean}\right]_i^2}{(n-1)}} \tag{5}$$

Greenwich mean time (GMT) of sighting measurement.- The GMT of each sighting measurement was computed as follows:

$$\left.\begin{aligned} GMT &= T_L + \Delta T_G \\ T_L &= \text{Gemini XII launch time} \\ &= 20 \text{ hr } 46 \text{ min } 33.419 \text{ sec GMT} \\ &\quad\ \text{November 11, 1966} \\ \Delta T_G &= \text{Gemini elapsed time from } T_L \end{aligned}\right\} \tag{6}$$

Window-induced measurement error.- Deformation of the surfaces of the window panes of the Gemini spacecraft (due to manufacture, and pressure and temperature environment in flight) causes deviations in the sextant LOS resulting in errors in the measured sextant angles. Line-of-sight deviations determined both experimentally and analytically have been used in this report to correct the measured data. An important factor in correcting the experimental data was the point on the window at which each sextant LOS intersected the window surface (see p. 11). The intersection points were used in an experimental laboratory setup and an analytical program to determine the average sextant LOS locations for each sextant sighting period and the angles and planes of incidence of each LOS with respect to the window axis system. It was estimated by the spacecraft crew that the position of the sextant LOS through the window could be determined to about ±1/2 inch. Analysis has indicated that this uncertainty in position could result in a maximum uncertainty in the sextant measurement error of about ±2 to 3 arc sec.

TEST CONDITIONS

The T002 experiment was successfully completed on orbits 40, 48, 54, 55, and 56 of the Gemini XII flight. The spacecraft position (latitude, longitude, and altitude) as a function of time (GMT) for each orbit is given in table I.

Sighting Targets

The stars Betelgeuse and Rigel were the measurement targets during the sighting periods on orbits 40, 48, and 56. Betelgeuse and Bellatrix were the measurement targets for the sighting periods 54 and 55. The celestial angle θ_S between Betelgeuse and Rigel and Betelgeuse and Bellatrix were 18°36'17" and 7°31'47", respectively. These angles were computed from the known values of right ascension and declination of each target; they are corrected for annual aberration and have been shown to be less than 1 arc sec in error. Measurements between the moon limb and a star were also planned for this flight, but the moon was a thin crescent that was available as a sighting for only a short time after spacecraft sunset. Although the star/star target configuration used is an idealized non-navigation type target pair, a substantial portion of the experiment objectives were still met.

Suit Configuration

The pilot wore a standard Gemini type pressure suit with gloves and helmet off during all sighting periods except the last. During orbit 56, he donned the pressure suit helmet, inserted the long eye relief eyepiece in the sextant, and performed the measurement sequence.

Spacecraft Interior Lighting

During the sighting period, the spacecraft was completely dark except for a shaded red utility light permitting the command pilot to write down the data and read his elapsed time clock. The sextant readout counter was illuminated with a red light, which was turned on only as required.

Vehicle Attitude Rates

The vehicle attitudes measured with respect to a stable platform were used to compute the vehicle attitude rates. Prior to the sighting period the platform was alined with respect to the local vertical and the spacecraft orbit plane and was torqued in the orbit plane (pitch) at a rate of about 4.0°/min, the orbital rate at about 150 miles altitude. Figure 8 is a typical time history of the variation of the vehicle attitudes for the Gemini elapsed time corresponding to the sighting measurements numbers 14, 15, 16, and 17 of sighting period 1 (orbit 40). Due to a shortage of spacecraft electrical power, this is the only sighting period during which the stable

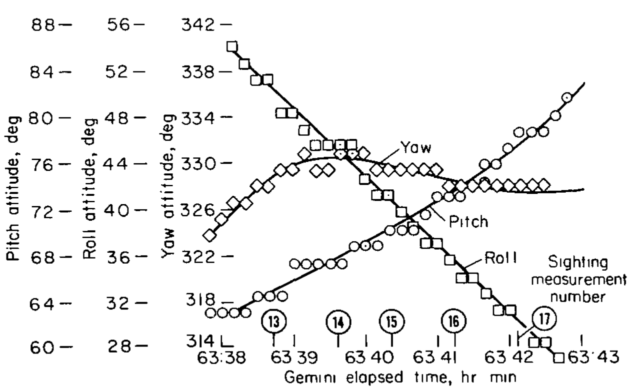

Figure 8.- Typical vehicle attitudes during sextant sighting period number 1 (Orbit 40).

platform reference was available for measurement of vehicle rates and attitudes. However, the command pilot assured the experimenters that it was typical of all the sighting periods.

It can be seen from figure 8 that the spacecraft is well stabilized in pitch and yaw with maximum rates of 2° and 4°/min, respectively, while the roll rate during these sighting measurements was about constant at 5°/min. There was little effect of attitude rate on sextant measurement performance at rates of 1.5°/sec (ref. 8); therefore, at these rates of less than 0.1°/sec, performance should not be affected.

RESULTS AND DISCUSSION

The results of the T002 experiment consist of learning curve data obtained during the initial period of training with the sextant, baseline data for comparison with flight results, and inflight data obtained during the Gemini XII flight.

Initial Training

The Gemini XII pilot was trained as described previously. The standard deviation of the measurement error from its mean value was used as the measure of the pilot's proficiency. The standard deviation varied from a maximum of about ±13 arc sec early in the training period to a minimum of about ±4 arc sec toward the end.

The training data of reference 7 for a large group of subjects indicated that the range of standard deviation of sighting measurements at the end of a 2-week period was about 14 arc sec. The T002 training data, however, were obtained from an exceptionally talented operator who used an 8-power sextant. In addition, the sextant used in obtaining the T002 training data is a vastly improved instrument optically and mechanically, over that used in reference 7. The lower standard deviation for the T002 training data compared with that of reference 7 may also be due partially to the increase in magnification from 3.0 to 8.0.

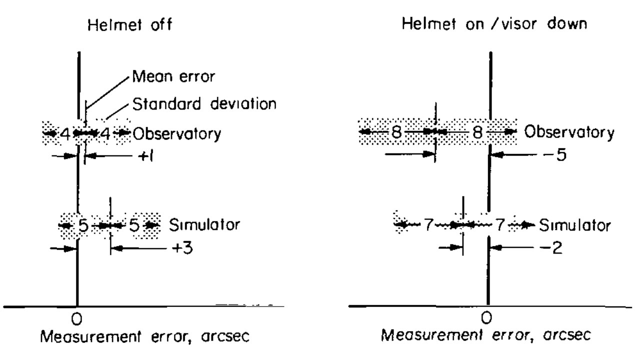

Figure 9.- Preflight baseline data, T002 experiment; Ames navigation simulator and ground sighting station; star/star targets.

Baseline Data - Star/Star Targets

Sextant measurements were made with the helmet off (normal eye relief eyepiece) and helmet on, visor down (long eye relief eyepiece). Figure 9 summarizes the standard deviation of the sighting measurement errors about their mean value (the shaded bars) and the mean sighting measurement error (the offset line) for all sighting periods; the sighting measurement error is plotted as the abscissa.

The figure also summarizes baseline data obtained at a ground sighting station using real stars. The sighting measurement error is corrected for annual aberration and atmospheric refraction. The standard deviations of the sighting measurement errors obtained with the helmet off, both in the simulator and from the ground observatory using actual stars, agree well with values of ±5 and ±4 arc sec, respectively. Similar measurements with the helmet on and visor down, both in the simulator and from the observatory, also agree well, having standard deviations of ±7 and ±8 arc sec, respectively. The mean sighting measurement errors are small, ranging from 1 to 5 arc sec.

Gemini XII In-Flight Data

The Gemini XII in-flight sextant measurements were, as noted previously, made from within the stabilized spacecraft while the pilot was looking through the right-hand window, which was of good optical quality. The measurement data are presented in table II. The standard deviation of the sighting measurement errors and the mean sighting measurement error are summarized in figure 10 where the sighting measurement error is again plotted as the abscissa. For the first four sighting periods, the measurements were made with the helmet off. The standard deviation for these sighting periods was less than ±9 arc sec, and the average standard deviation for all four sighting periods was 7 arc sec. The measurement bias errors for the first two sighting periods in which Betelgeuse and Rigel were used as targets were -2 and 0 arc sec, respectively, whereas the measurement bias errors for sighting periods 3 and 4, in which Betelgeuse and Bellatrix were used as targets, were -4 and -2 arc sec, respectively. The average mean sighting measurement error for all four periods was -2 arc sec. During the fifth sighting period, the measurements were made with the helmet on, visor down, and with the long eye relief eyepiece installed in the sextant. The standard deviation of measurement errors for these measurements was 8 arc sec, while the mean sighting measurement error was -11 arc sec.

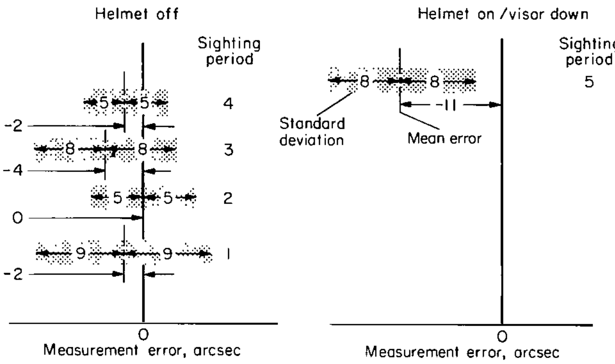

Figure 10.- In-flight sighting measurement data T002 experiment; Gemini XII spacecraft; star/star targets.

The standard deviation of the measurements for all sighting conditions is below 9 arc sec, agreeing well with the baseline data. The mean sighting measurement errors of the in-flight data are generally small, less than 4 arc sec for the helmet off configuration, which also agrees well with the baseline data. The large mean sighting measurement error, ε_{mean}, for the helmet on configuration data (orbit 56) is inconsistent with both the preflight baseline data and the other in-flight data. The mean sighting measurement error, ε_{mean} comprises many components as indicated in equations (1) to (4). The magnitudes of these error components for this set of data were carefully scrutinized in an effort to explain the inconsistency. All the error components seemed reasonable except the mean zero bias measurement error $(\theta_z)_{mean}$ (table III), which had both a large mean value and a large standard deviation. This large standard deviation indicates that the mean zero bias measurement error $(\theta_z)_{mean}$ is not well known and the significance of the large mean sighting measurement error, ε_{mean}, may therefore be open to question.

The mean sighting errors presented here are corrected for window-induced measurement errors, for errors due to the difference of the index of refraction of the light-transmitting media within and outside the spacecraft, for measured zero bias, and for instrument calibration.

Subjective Comments

The pilot stated that, in general, the operation of the T002 sextant in zero g was much simpler and easier to manage than had been anticipated from his preflight training and simulation. During training, the pilot indicated that the weight of the sextant caused fatigue, but this was alleviated in the weightless environment of actual space flight. He also stated that acquisition of the star patterns for the experiment was marginal with the restricted field of view of the window. A larger window in the spacecraft and easier access to it would probably simplify acquisition of the star patterns.

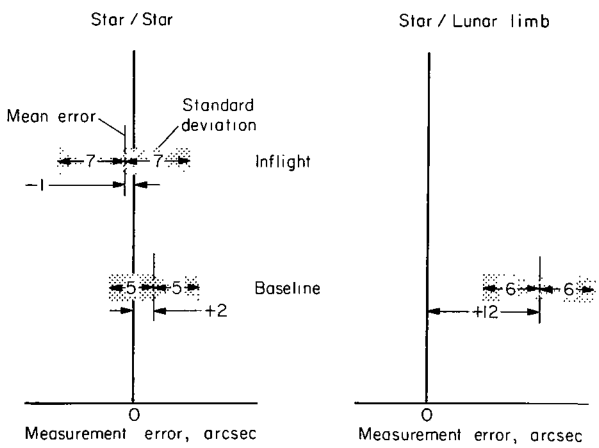

Figure 11.- Comparison of in-flight and baseline data, T002 experiment; helmet off.

Comparison of Baseline and Flight Data

The pilot's performance as indicated by the baseline data was virtually the same as that in the space-flight environment as seen in figure 11, thus indicating the usefulness of simulators and earth-based observatories in evaluating space navigation measurement techniques. Figure 11 shows that navigation type measurements (star/lunar limb) were made with a standard deviation of ±6 arc sec in the simulator. In-flight data to support this performance await future flights.

Space Navigation Using a Hand-Held Sextant

For the Apollo lunar mission the primary spacecraft navigation system will utilize earth-based radar tracking measurements. A simplified on-board backup system is still desirable, however, in which the hand-held sextant could be a key element. The minimum functions of backup system hardware are: (1) to make angular navigation measurements; (2) to provide a reference for holding spacecraft attitude during a velocity correction; and (3) possibly to provide a reference for alining an inertial measurement unit to measure the ΔV applied. The sextant obviously is designed to measure angles with good accuracy. The sextant with a lighted reticle could also perform functions 2 and 3 if it were mounted on a bracket at the spacecraft window and boresighted with the spacecraft axes. Such a mount in the Gemini XII spacecraft appeared to perform satisfactorily during rendezvous.

Preliminary studies at Ames have indicated that with only a simple collimated reticle on the spacecraft window it is possible to hold the spacecraft attitude manually with sufficient accuracy to perform a velocity correction. The sextant with 8-power magnification should improve this performance. Alining an inertial measurement unit by this technique has not been studied.

Results of both the D-9 autonomous orbit navigation in-flight experiment (ref. 5) on Gemini VII and the NASA rendezvous navigation experiment on Gemini VI (ref. 6) indicate that the hand-held sextant is suitable for navigation in these flight phases.

This experiment has shown that satisfactory navigation measurements for several phases of space-flight (e.g., midcourse, rendezvous, earth orbit) can be made using a hand-held sextant. Therefore, it appears that the hand-held sextant could be used to implement an autonomous on-board navigation system.

It is recognized that the sextants used in these tests are experimental instruments manufactured to prove the design concept. Design changes may be necessary to provide an instrument compatible with the operational system requirements.

CONCLUSIONS

From an inspection of the results of the in-flight spacecraft experiments presented, it may be concluded that:

1. The angle between stars can be measured with a hand-held sextant. The total measurement error (astronaut + sextant + spacecraft window) had a standard deviation of less than ±10 arc sec and an average mean sighting measurement error of only 2 arc sec.

2. Sextant measurements of the angle between stars with the helmet on, visor down, indicate that the standard deviation of sighting measurement errors was less than ±10 arc sec.

3. The T002 in-flight data and the preflight baseline data obtained in the simulator and from ground observatories were almost identical. It appears that at least for the conditions of this experiment, simulators and ground observatories can be useful in evaluating space navigation measurement techniques.

4. In-flight experience has demonstrated the potential of the hand-held sextant for use in midcourse navigation (NASA T002 experiment), orbit navigation (Air Force D-9 experiment), and rendezvous navigation (NASA rendezvous experiment on Gemini VI).

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., 94035, Aug. 20, 1968
125-17-02-10-00-21

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TABLE I.- SPACECRAFT ORBITAL POSITION

Orbit 40; November 14, 1966				Orbit 48; November 15, 1966			
Greenwich mean time, hr:min:sec	Latitude, deg	Longitude, deg	Altitude above an oblate earth, n mi	Greenwich mean time, hr:min:sec	Latitude, deg	Longitude, deg	Altitude above an oblate earth, n mi
12:01:16	2.12N	101.00E	140.81	00:03:30	4.83S	71.22W	140.51
12:03:25	2.03S	108.00E	140.59	00:05:30	8.65S	64.58W	140.61
12:05:14	5.58S	114.00E	140.63	00:07:30	12.33S	57.80W	140.92
12:07:20	9.57S	121.00E	140.91	00:09:30	15.81S	50.83W	141.43
12:09:23	13.30S	128.00E	141.42	00:11:30	19.02S	43.60W	142.10
12:11:23	16.68S	135.00E	142.12	00:13:30	21.90S	36.10W	142.92
12:13:18	19.70S	142.00E	142.93	00:15:30	24.38S	28.29W	143.84
12:15:09	22.30S	149.00E	143.84	00:17:30	26.38S	20.19W	144.83
12:17:11	24.73S	157.00E	144.92	00:19:30	27.85S	11.84W	145.85
12:19:09	26.63S	165.00E	146.03	00:21:30	28.73S	03.29W	146.87
12:21:18	28.08S	174.00E	147.26	00:23:30	29.02S	05.34E	147.87
12:23:10	28.82S	178.00W	148.31	00:25:30	28.68S	13.97E	148.82
12:25:15	28.98S	169.00W	149.44	00:27:30	27.73S	22.48E	149.70
12:27:21	28.48S	160.00W	150.51	00:29:30	26.21S	30.78E	150.52
12:29:14	27.47S	152.00W	151.39	00:31:30	24.12S	38.83S	151.25
12:31:10	25.92S	144.00W	152.01	00:33:30	21.67S	46.57E	151.91
12:33:11	23.85S	136.00W	152.98	00:35:30	18.78S	54.01E	152.50

TABLE I.- SPACECRAFT ORBITAL POSITION - Continued

Orbit 54; November 15, 1966				Orbit 55; November 15, 1966			
Greenwich mean time, hr:min:sec	Latitude, deg	Longitude, deg	Altitude above an oblate earth, n mi	Greenwich mean time, hr:min:sec	Latitude, deg	Longitude, deg	Altitude above an oblate earth, n mi
10:31:30	3.32S	125.28E	140.68	12:01:30	3.67S	102.89E	140.48
10:33:30	7.17S	131.88E	140.60	12:03:30	7.51S	109.50E	140.33
10:35:30	10.91S	138.60E	140.73	12:05:30	11.24S	116.23E	140.40
10:37:30	14.47S	145.48E	141.06	12:07:30	14.79S	123.14E	140.67
10:39:30	17.80S	152.61E	141.58	12:09:30	18.09S	130.29E	141.12
10:41:30	20.82S	160.01E	142.25	12:11:30	21.08S	137.71E	141.74
10:43:30	23.46S	167.70E	143.03	12:13:30	23.68S	145.43E	142.46
10:45:30	25.65S	175.68E	143.90	12:15:30	25.83S	153.45E	143.29
10:47:30	27.33S	176.05W	144.84	12:17:30	27.47S	161.74E	144.19
10:49:30	28.46S	167.70W	145.79	12:19:30	28.54S	170.24E	145.11
10:51:30	28.98S	158.95W	146.74	12:21:30	29.01S	178.87E	146.03
10:53:30	28.88S	150.31W	147.65	12:23:30	28.85S	172.48W	146.94
10:55:30	28.17S	141.73W	148.52	12:25:30	28.08S	163.92W	147.81
10:57:30	26.87S	133.33W	149.33	12:27:30	26.72S	155.53W	148.63
10:59:30	25.02S	125.18W	150.08	12:29:30	24.83S	147.40W	149.40
11:01:30	22.70S	117.32W	150.77	12:31:30	22.45S	139.56W	150.13
11:03:30	19.95S	109.76W	151.41	12:33:30	19.67S	132.02W	150.80
11:05:30	16.85S	102.48W	151.98	12:35:30	16.53S	124.78W	151.43
11:07:30	13.46S	95.48W	152.52				

TABLE I.- SPACECRAFT ORBITAL POSITION - Concluded

Orbit 56; November 15, 1966			
Greenwich mean time, hr:min:sec	Latitude, deg	Longitude, deg	Altitude above an oblate earth, n mi
13:31:30	4.02S	80.51E	140.46
13:33:30	7.86S	87.12E	140.31
13:35:30	11.58S	93.87E	140.39
13:37:30	15.61S	100.81E	140.66
13:39:30	18.38S	107.98E	141.12
13:41:30	21.34S	115.42E	141.73
13:43:30	23.91S	123.17E	142.43
13:45:30	26.01S	131.22E	143.28
13:47:30	27.59S	139.53E	144.17
13:49:30	28.61S	148.05E	145.24
13:51:30	29.01S	156.68E	146.14
13:53:30	28.80S	165.32E	147.01
13:55:30	27.97S	173.88E	147.85
13:57:30	26.57S	177.76W	148.64
13:59:30	24.62S	169.65W	149.38
14:01:30	22.21S	161.84W	150.07
14:03:30	19.39S	154.33W	150.71
14:05:30	16.22S	147.12W	151.32
14:07:30	12.79S	140.15W	151.89

TABLE II.- IN-FLIGHT SEXTANT SIGHTING DATA, T002 EXPERIMENT, GEMINI XII

Orbit 40

Sighting targets:

Primary LOS - Betelgeuse
Scanning LOS - Rigel
Zero bias measurement - Aldebaran

Suit configuration: Helmet off

Measurement		Gemini elapsed time hr:min:sec	Sextant readout angle, deg	Cabin temp., °F	Cabin pressure, psi
Zero bias	1	63:19:08.0	00.001	77.5	5.26
	2	63:20:18.0	00.002		
	3	63:21:33.5	99.999		
	4	63:22:09.0	00.000		
	5	63:22:53.5	00.001		
Two stars	6	63:28:22.0	18.611		
	7	63:30:31.5	18.606		
	8	63:31:38.5	18.604		
	9	63:32:53.0	18.608		
	10	63:34:27.0	18.604		
	11	63:35:26.0	18.604		
	12	63:37:13.5	18.609		
	13	63:38:46.0	18.606		
	14	63:39:36.5	Void		
	15	63:40:21.0	18.608		
	16	63:41:15.0	18.611		
	17	63:42:07.0	18.605		
	18	63:43:53.0	18.605		
	19	63:44:51.0	18.605		
	20				

Orbit 48

Sighting targets:

Primary LOS - Betelgeuse
Scanning LOS - Rigel
Zero bias measurement - Aldebaran

Suit configuration: Helmet off

Measurement		Gemini elapsed time hr:min:sec	Sextant readout angle, deg	Cabin temp., °F	Cabin pressure, psi
Zero bias	1	75:20:14.5	99.995	77.5	5.26
	2	75:21:06.5	99.995		
	3	75:21:45.0	99.995		
	4	75:22:35.0	00.005		
	5	75:23:29.0	00.003		
Two stars	6	75:28:44.0	18.604	76.9	
	7	75:29:25.0	18.605		
	8	75:30:28.0	18.608		
	9	75:31:12.5	18.605		
	10	75:32:00.0	18.609		
	11	75:33:15.5	18.604		
	12	75:35:26.5	18.608		
	13	75:36:11.0	18.606		
	14	75:36:53.5	18.606		
	15	75:37:39.0	18.605		
	16	75:39:00.0	18.604	76.3	
	17	75:39:33.5	18.605		
	18	75:40:29.0	18.606		
	19	75:41:11.0	18.604		
	20				

TABLE II.- IN-FLIGHT SEXTANT SIGHTING DATA, T002 EXPERIMENT, GEMINI XII - Continued

Orbit 54

Sighting targets:

Primary LOS - Betelgeuse
Scanning LOS - Bellatrix
Zero bias measurement - Aldebaran

Suit configuration: Helmet off

Measurement		Gemini elapsed time hr:min:sec	Sextant readout angle, deg	Cabin temp., °F	Cabin pressure, psi
Zero bias	1	85:50:06.5	00.002	71.3	5.29
	2	85:51:06.0	00.001		
	3	85:51:49.5	00.000		
	4	85:52:31.0	00.002		
	5	85:53:15.5	00.005		
Two stars	6	86:02:05.5	07.536		
	7	86:03:51.0	07.531		
	8	86:04:56.0	07.529		
	9	86:05:57.5	07.530		
	10	86:06:56.0	07.529		
	11	86:07:51.5	07.528		
	12	86:08:53.0	07.528		
	13	86:09:31.0	07.528		
	14	86:11:02.0	07.531		
	15	86:13:23.5	07.529		
	16	86:14:35.0	07.528		
	17	86:15:56.0	07.529		
	18	86:17:03.0	07.528		
	19	86:17:50.0	07.531		
	20	86:18:53.5	07.531		

Orbit 55

Sighting targets:

Primary LOS - Betelgeuse
Scanning LOS - Bellatrix
Zero bias measurement - Aldebaran

Suit configuration: Helmet off

Measurement		Gemini elapsed time hr:min:sec	Sextant readout angle, deg	Cabin temp., °F	Cabin pressure, psi
Zero bias	1	87:19:23.5	00.005	70.6	5.26
	2	87:20:24.0	00.002		
	3	87:20:53.5	00.000		
	4	87:22:28.0	99.995		
	5	87:23:15.5	00.003		
Two stars	6	87:25:49.5	07.529		
	7	87:27:16.3	07.531		
	8	87:28:29.5	07.532		
	9	87:29:28.0	07.529		
	10	87:30:13.5	07.529		
	11	87:31:35.0	07.530		
	12	87:32:24.0	07.529		
	13	87:33:14.0	07.529		
	14	87:33:45.0	07.528		
	15	87:35:02.0	07.529		
	16	87:35:50.5	07.530		
	17	87:36:30.0	07.529		
	18	87:37:27.0	07.529		
	19	87:38:06.0	07.532		
	20	87:38:54.0	07.529		

TABLE II.- IN-FLIGHT SEXTANT SIGHTING DATA, T002 EXPERIMENT, GEMINI XII - Concluded

Orbit 56

Sighting targets:

Primary LOS - Betelgeuse
Scanning LOS - Rigel
Zero bias measurement - Aldebaran

Suit configuration: Helmet on, Visor down

Measurement		Gemini elapsed time hr:min:sec	Sextant readout angle, deg	Cabin temp., °F	Cabin pressure, psi
Zero bias	1	88:48:53.0	00.003	70.0	5.26
	2	88:49:30.0	00.009		
	3	88:50:29.1	00.007		
	4	88:51:15.5	99.995		
	5	88:51:59.5	00.003		
Two stars	6	88:58:03.0	18.605		
	7	88:58:28.5	18.605		
	8	88:59:01.0	18.604		
	9	88:59:32.0	18.607		
	10	89:00:10.0	18.607	70.6	
	11	89:00:48.3	18.607		
	12	89:01:33.0	18.608		
	13	89:02:19.0	18.610		
	14	89:03:10.5	18.607		
	15	89:04:05.1	18.611		
	16	89:04:57.1	18.610		
	17	89:05:27.0	18.610		
	18	89:06:09.0	18.607		
	19	89:06:43.0	18.609		
	20	89:07:44.5	18.609		

TABLE III.- SUMMARY OF SIGHTING MEASUREMENT DATA

Orbit	Type of measurement	Mean value and standard deviation of measurement error, arc sec		Window induced measurement error, ε_W	Sextant calibration error, ε_c, arc sec	Corrected mean measurement error, ε_{mean}, arc sec
40	Zero bias	Mean Standard deviation	+2.2 ±4.1	-1.6	0	
	Two star	Mean Standard deviation	+5.8 ±9.0	+0.4	-4	-2.4
48	Zero bias	Mean Standard deviation	-5.0 ±18.0	-7.6	0	
	Two star	Mean Standard deviation	+1.4 ±5.4	-4.8	-4	-0.4
54	Zero bias	Mean Standard deviation	+6.8 ±6.8	-9.7	0	
	Two star	Mean Standard deviation	-1.1 ±7.6	-9.5	+4	-4.5
55	Zero bias	Mean Standard deviation	+3.6 ±13.7	-9.7	0	
	Two star	Mean Standard deviation	-1.8 ±4.5	-9.5	+4	-1.6
56	Zero bias	Mean Standard deviation	+13.7 ±19.3	-7.6	0	
	Two star	Mean Standard deviation	+9.7 ±7.5	-4.8	-4	-10.8

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